Mon. Not. R. Astron. Soc. **308**, L29–L33 (1999)

On the anomalous X-ray afterglows of GRB 970508 and 970828

M. Vietri,[1] C. Perola,[1] L. Piro[2] and L. Stella[3★]
[1]*Università di Roma 3, Via della Vasca Navale 84, 00147 Roma, Italy*
[2]*Istituto di Astrofisica Spaziale, 00040 Frascati, Roma, Italy*
[3]*Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monte Porzio Catone, Roma, Italy*

Accepted 1999 June 24. Received 1999 June 21; in original form 1999 May 5

ABSTRACT

Recently, *BeppoSAX* and *ASCA* have observed an unusual resurgence of soft X-ray emission during the afterglows of GRB 970508 and 970828, together with marginal evidence for the existence of Fe lines in both objects. We consider the implications of the existence of a torus of iron-rich material surrounding the sites of gamma-ray bursts, as would be expected in the supra-nova model; in particular, we show that the fireball will quickly hit this torus, and bring it to a temperature of $\approx 3 \times 10^7$ K. Bremsstrahlung emission from the heated-up torus will cause a resurgence of the soft X-ray emission with all expected characteristics (flux level, duration and spectral hardening with time) identical to those observed during the re-burst. Also, thermal emission from the torus will account for the observed iron line flux. These events are also observable, for instance by new missions such as *SWIFT*, when beaming away from our line of sight makes us miss the main burst, as fast (soft) X-ray transients, with durations of $\approx 10^3$ s and fluences of $\approx 10^{-7}$–10^{-4} erg cm^{-2}. This model provides evidence in favour of the supra-nova model for gamma-ray bursts.

Key words: line: formation – supernova remnants – gamma-rays: bursts – X-rays: general.

1 INTRODUCTION

The discovery of afterglows from gamma-ray bursts has greatly strengthened our confidence in the correctness of the fireball model (Rees & Mészáros 1992). Since then, attention has begun to shift toward the nature of the exploding source, a problem which is conveniently decoupled from the fireball itself and the ensuing afterglow. For this reason, evidence on the nature of the source has to be sought elsewhere. In particular, attention has been drawn to the possible interaction of the burst with surrounding material, and the possible generation of a detectable Fe line in soft X-rays (Perna & Loeb 1998; Mészáros & Rees 1998; Boettcher et al. 1999; Ghisellini et al. 1999).

Recently, a re-burst, i.e. a resurgence of emission during the afterglow, has been reported in two bursts, GRB 970508 (Piro et al. 1998) and GRB 970828 (Yoshida et al. 1999). In the case of GRB 970508, the re-burst occurs about 10^5 s after the burst, with the soft X-ray flux clearly rising, and departing from its otherwise typical power-law decline. This resurgence lasts a total of $\approx 4 \times 10^5$ s, reaches a typical flux in the *BeppoSAX* band of $\approx 8 \times 10^{-13}$ erg s^{-1} cm^{-2}, after subtraction of the normal afterglow, and shows evidence for a harder spectrum than during the afterglow proper (power-law photon index of $\alpha = 0.4 \pm 0.6$, as opposed to $\alpha = 1.5 \pm 0.6$ before the re-burst, and $\alpha = 2.2 \pm 0.7$ at the end of the re-burst) (Piro et al. 1998, 1999).

Furthermore, possible evidence for the existence of Fe K-shell emission lines has been found in these same two bursts: for GRB 970508 see Piro et al. (1999), while for GRB 970828 see Yoshida et al. (1999). In the first case, a Kα iron line occurs at an energy compatible with the optically determined redshift of the burst, while in the second case, for which no independent redshift determination exists, the line, if interpreted as Kα from neutral or weakly ionized iron, yields a redshift of $z = 0.33$. What are astonishing are the inferred line fluxes and equivalent widths: for GRB 970508, $F = (2.8 \pm 1.1) \times 10^{-13}$ erg s^{-1} cm^{-2} (EW $\approx$1.1 keV); for GRB 970828, $F = (1.5 \pm 0.8) \times 10^{-13}$ erg s^{-1} cm^{-2} (EW $\approx$3 keV). In the case of GRB 970508, furthermore, no evidence for the Fe line was found after about 10^5 s.

Despite their inferred intensities, these lines are at the limit of *BeppoSAX* and *ASCA* detectability, so that further observations are needed to confirm their presence. In contrast, the statistical significance of the re-bursts is very robust. In the following, we shall concentrate on the particularly well-documented case of GRB 970508, keeping in mind that qualitatively similar arguments apply to GRB 970828 as well.

It is the aim of this paper to show that, if enough material of sufficiently high density is present in the surroundings of the gamma-ray burst event site, then this re-burst is exactly what one ought to expect on theoretical grounds. In particular, it is possible

★ Affiliated to ICRA.

to explain all observed characteristics of the re-burst, such as duration, flux level and spectral hardening, including the (possible) presence of the iron lines. In the next section we shall consider the dynamical interaction of the ejecta of the burst with the torus, and in the following one we shall discuss the thermodynamic state of the torus, and establish the properties of its (thermal) emission. In the discussion section, it will also be pointed out that the thermodynamic status of the torus is precisely the same as *postulated* by Lazzati, Campana & Ghisellini (1999) to explain the properties of the iron line.

2 DYNAMICAL INTERACTION WITH SURROUNDING GAS

Both Piro et al. (1999) and Lazzati et al. (1999) have already argued that the material giving rise to the Fe K line cannot lie on the line of sight: the ensuing column depths in H and Fe would give effects that are easy to observe. Furthermore, this material should be present in large amounts which would spoil the smooth, power-law expansion of the afterglow which is observed to last more than a year. We thus begin by assuming that the site of the explosion is surrounded by a thick torus of matter, with an empty symmetry axis pointing roughly toward the observer. The particle density n and distance R from the explosion site will be scaled in units of $10^{10}\,\mathrm{cm}^{-3}$ and $10^{16}\,\mathrm{cm}$.

A time R/c after the explosion, this torus will be inundated by the burst proper, and a few seconds later ($\delta t \approx R/\gamma^2 c = 30\,\mathrm{s}$, where $\gamma = 100$ is the shell bulk Lorenz factor) it will be hit by the ejecta shell. This crash will generate a forward shock propagating into the torus, and a reverse one moving into the relativistic shell. For any reasonable value of the torus density, the forward shock will quickly rake up as much mass as there is in the shell; we find that this occurs after the shock has propagated a mere distance d, with

$$d = 6\times 10^{8}\,\mathrm{cm}\,\frac{E}{10^{51}\,\mathrm{erg}}\,\frac{10^{10}\,\mathrm{cm}^{-3}}{n}\left(\frac{10^{16}\,\mathrm{cm}}{R}\right)^{2}\frac{100}{\gamma}. \tag{1}$$

As is well known, this means that the relativistic shell must slow down to subrelativistic speeds. Thus, after just $d/c \approx 0.1\,\mathrm{s}$, the forward shock has become subrelativistic. The large pressure behind the forward shock acts to steepen the reverse shock, which will thus slow down the incoming material to subrelativistic speeds as well. All of this occurs a few seconds after the burst reaches the torus.

The total energy released is expected to be of the order of the whole kinetic energy of the shell, because post-shock acceleration of electrons occurs at the expense of the shell bulk expansion, in the shocks. If we suppose that the burst generated a total energy release of $E = 10^{51}$ erg, that the initial burst is roughly isotropic, and that the torus covers $\delta\Omega$ rad as seen from the explosion site, the total energy release E_{sh} will be

$$E_{\mathrm{sh}} = \frac{\delta\Omega}{4\pi}E. \tag{2}$$

The total emission time-scale can also be reliably computed: the reader will have already noticed that this emission scenario is similar to the external shock scenario (Mészáros, Laguna & Rees 1993), except for two differences. First, in the external shock scenario we are seeing the burst from a reference frame that is moving with respect to the shell of shocked gas with large Lorentz factor, while here the observer is sitting in a reference frame in which the shocked gas is moving subrelativistically. The major consequence of this first difference is that the photon emission will be isotropic, and we shall thus see it, even though the initial shell movement was perpendicular to the line of sight. The second difference is that, in the external shock scenario, it is matter ahead of the forward shock that is moving relativistically with respect to the shocked gas, while matter entering the reverse shock is moving only barely relativistically with respect to it. In this paper, instead, the opposite applies: matter entering the reverse shock is relativistic, while the forward shock is barely, if at all, relativistic.

Still, these two differences do not spoil the fact that electrons accelerated at either shock cool much faster than the shell light-crossing time, as shown by Mészáros et al. (1993), so that the total burst duration is given by the time that the reverse shock takes to cross the whole shell. In our model, the shell thickness in the laboratory frame is $\approx R/\gamma$ (Mészáros et al. 1993), and, since the reverse shock is relativistic with respect to the incoming matter, the shock crossing time, and thus also the duration t_{sec} of the secondary burst, is given by

$$t_{\mathrm{sec}} = \frac{R}{\gamma c} = 3\times 10^{3}\,\mathrm{s}\,\frac{R}{10^{16}\,\mathrm{cm}}. \tag{3}$$

Together, the total energy release and emission time-scale give us the expected bolometric luminosity; the observed flux can be computed, for cosmological parameters $\Omega = 1$, $H_0 = 65\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $\Lambda = 0$, and the burst redshift $z = 0.835$ (Metzger et al. 1997), and is

$$F_{\mathrm{X}} = 1.5\times 10^{-10}\,\mathrm{erg\,s^{-1}\,cm^{-2}}\quad \frac{\delta\Omega}{4\pi}\,\frac{E}{10^{51}\,\mathrm{erg}}\,\frac{10^{16}\,\mathrm{cm}}{R}. \tag{4}$$

We must now establish in which band this emission will end up. As is well known, the spectra of bursts are highly variable, both from burst to burst and within the same burst, at different moments. Also, the fireball model is not too specific about the spectral characteristics of bursts. We can still get an idea of the spectrum, however, by noticing first that it will be non-thermal, with the usual power-law dependence upon photon energy typical of synchrotron emission, and secondly that once again we are observing a burst in the external shock scenario, but in the shell frame. In normal bursts, the spectrum has a break at an energy ϵ_{b}, which is approximately $\epsilon_{\mathrm{b}} \approx 1\,\mathrm{MeV}$. However, this spectral feature is blueshifted in the observer's frame by the bulk Lorentz factor of the shell: $\epsilon_{\mathrm{b}} = \gamma\epsilon_{\mathrm{i}}$. The intrinsic spectral break ϵ_{i}, i.e. in the shell frame, is thus given by

$$\epsilon_{\mathrm{i}} = \frac{\epsilon_{\mathrm{b}}}{\gamma} = 10\,\mathrm{keV}\,\frac{\epsilon_{\mathrm{b}}}{1\,\mathrm{MeV}}\,\frac{100}{\gamma}. \tag{5}$$

It is clear why this secondary burst was not observed. First of all, it is dimmer than the original one by a bolometric factor of $\delta\Omega/4\gamma\pi < 10^{-2}$, which would push it below the detection threshold for both BATSE and the GRBM/WFC instruments of *BeppoSAX*. Also, it must have occurred sometime between the burst proper and the *BeppoSAX* detection of the iron line, when, however, *BeppoSAX* was not observing with its (more sensitive) narrow-field instruments.

The further evolution of the shocked shell is as follows. The material that passed through the reverse shock will have an internal energy density higher than the pre-shock one by a factor of Γ^2, where $\Gamma \approx \gamma$ is the Lorentz factor of the reverse shock, as seen by the pre-shock ejecta shell. For reasonable radiative efficiencies, the post-shock matter will have a relativistic velocity dispersion even after the secondary burst; then, a rarefaction wave will make it expand at the sound speed $\approx c/\sqrt{3}$ back into the cavity from which it came. Thus pressure behind the forward shock will be reduced on a time-scale $\approx \delta R/c$, where we can again take for the post-reverse shock shell thickness, as an order-of-magnitude estimate, $\delta R \approx R/\gamma$. Thus the heated gas expansion time-scale is again $\approx R/\gamma c \approx 3\times 10^3$ s.

As the pressure from the post-reverse shock material is reduced, the forward shock keeps propagating because of momentum conservation. However, even this shock cannot last long, because of the strong counterpressure applied by the pre-shock torus. We shall show in the next section that this material will be brought up to $T_{\rm f} \approx 10^8$ K by heating/cooling from the primary and secondary bursts. Then it can easily be checked that $\rho_{\rm s}c^2 \approx m_{\rm p}nv^2$, where $\rho_{\rm s}$, the shell baryon density, is given by spreading the total fireball baryon mass, $E/\gamma c^2$, over the shell volume, $4\pi R^3/\gamma$, and the velocity dispersion v of the torus is purely thermal: $v^2 = kT_{\rm f}/m_{\rm p}$. Thus the torus counterpressure will halt the forward shock as soon as it becomes subrelativistic.

We now make a small detour to discuss an interesting point about the kinematics. As seen from the observer, the part of the shell moving toward him will have moved a long distance ($\approx R$, taking the torus to be perpendicular to the line of sight) toward him before the torus is reached by the burst, and thus starts emitting. At that point, photons start travelling away from the torus, and they will catch up with the part of the expanding matter shell moving toward the observer at a rate

$$\delta R = (c - v)\delta t, \tag{6}$$

where $v \approx c(1 - 1/2\gamma^2)$ is the matter speed. However, the time appearing in the above equation is the time in the reference frame of the exploding object, which is related to that of the observer, $t_{\rm o}$, by $\delta t_{\rm o} = \delta t(1 - v/c)$, and thus the distance by which the photon catches up with the matter shell, in an observer's time interval $\delta t_{\rm o}$, is

$$\delta R = c\delta t_{\rm o}, \tag{7}$$

which is identical to the expression when relativistic effects are not present. This immediately allows us to estimate the distance of the torus: in fact, since the re-burst was present in the observations made $\approx 10^5$ s after the burst, and this can only occur after the burst photons have reached the torus, we deduce that $R(1 - \cos\theta) < 3\times 10^{15}$ cm, where R is the distance of the torus from the line of sight, and θ is the angle away from the line of sight of the torus symmetry plane. For the total distance, we shall take $R \approx 10^{16}$ cm.

3 THERMAL HISTORY OF THE TORUS

In order to proceed, we need first to determine the torus thickness, which we do by using a constraint from the observations of the iron line. When the torus is reached by the burst proper, the ionization parameter is

$$\xi \equiv \frac{L}{nR^2} = 10^9 \frac{L}{10^{51}\,\mathrm{erg\,s^{-1}}} \frac{10^{10}\,\mathrm{cm^{-3}}}{n} \left(\frac{10^{16}\,\mathrm{cm}}{R}\right)^2. \tag{8}$$

For these large values, we expect that all of the iron will be completely ionized, so that the generation of the iron line by fluorescence is unlikely. Furthermore, the torus will be hit by the secondary burst only $R/\gamma^2 c \approx 30$ s later; thus fluorescence with afterglow photons cannot be invoked either. The remaining mechanisms, multiple recombination/ionizations and thermal processes, both require a torus Thomson optical depth $\tau_{\rm T} \approx 1$ for maximum efficiency, and to avoid line smearing (fluorescence, instead, requires $\tau_{\rm T} \gg 1$). In such a thin shell, the torus temperature is quickly brought up by the primary burst photons to a level close to its inverse Compton value, given by $4kT_{\rm IC} = \bar{\epsilon}$, with $\bar{\epsilon}$ the average burst photon energy. Taking this to be of order the break photon energy $\epsilon_{\rm b} \approx 1$ MeV, we find $T \approx \epsilon_{\rm b}/4k \approx 3\times 10^9$ K. However, at this temperature, pair creation will quickly give $\tau_{\rm T} \gg 1$, and the ensuing thermal cooling will severely limit the temperature, to a value close to the pair creation limit,

$$T_{\rm IC} \approx 5\times 10^8\,\mathrm{K}. \tag{9}$$

At such large temperatures, the bremsstrahlung cooling time-scale is quite long: $t_{\rm br} \approx 5\times 10^5\,\mathrm{s}\ (10^{10}\,\mathrm{cm^{-3}}/n)(T/5\times 10^8\,\mathrm{K})^{1/2}$. However, the torus may cool as a result of inverse Compton cooling off the photons produced by the crashing of the ejecta on to the torus; these have a typical photon energy $\epsilon_{\rm i}$ (equation (5)) much below the torus temperature. For ease of reference, we shall call these secondary photons. The inverse Compton cooling time-scale, $t_{\rm IC} = 3m_{\rm e}c^2/8c\sigma_T U_{\rm ph}$ (where $m_{\rm e}$ is the electron mass, and $\sigma_{\rm T}$ the Thomson cross-section), can be computed using the fact that the photon energy density $U_{\rm ph} = L/cA$, where L, the luminosity of the secondary photons, is given by $L = E\delta\Omega/4\pi t_{\rm sec}$, and the total area is roughly twice the shock area, $A \approx 2R^2\delta\Omega$. We find thus that $U_{\rm ph} = E\gamma/8\pi R^3$, independently of the solid angle subtended by the torus. The ratio of the inverse Compton cooling time to the duration of the secondary burst is then given by

$$\frac{t_{\rm IC}}{t_{\rm sec}} = \frac{3\pi m_{\rm e}c^2R^2}{\sigma_{\rm T}E} = 1.3\left(\frac{R}{10^{16}\,\mathrm{cm}}\right)^2 \frac{10^{51}\,\mathrm{erg}}{E}. \tag{10}$$

We see that this ratio is very sensitive to the torus location, and to the total energetics. For $t_{\rm IC} \geq t_{\rm sec}$ the torus matter will remain hot (equation (9)), while for $t_{\rm IC} < t_{\rm sec}$ its temperature will cool to the new inverse Compton temperature of the secondary photon bath:

$$T_{\rm IC}^{(2)} \approx \frac{\epsilon_{\rm i}}{4k} \approx 3\times 10^7\,\mathrm{K}. \tag{11}$$

For the parameters assumed here, $t_{\rm IC} \approx t_{\rm sec}$, so that the torus will probably settle to a value intermediate between $T_{\rm IC}^{(2)}$ and $T_{\rm IC}$. We scale the value of T to $T_{\rm f} = 10^8$ K, but see the next section for a discussion.

The bremsstrahlung cooling time, at this lower temperature, is given by $t_{\rm br} \approx 1.3\times 10^5\,\mathrm{s}(10^{10}\,\mathrm{cm^{-3}}/n)$, comparable to the total duration of the re-burst observed by Piro et al. (1998). Also, the expected flux level is

$$F_{\rm br} = 1.1\times 10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}} \left(\frac{M}{1\,\mathrm{M_\odot}}\right)^2 \frac{10^{46}\mathrm{cm}^3}{V} \left(\frac{T}{10^8\,\mathrm{K}}\right)^{1/2}, \tag{12}$$

provided that the torus cooling time is longer than the torus light crossing time, $t_{\rm lc} \approx R/c$. Otherwise, the observed flux $F_{\rm br}^{\rm (obs)}$ would be related to the previous formula by

$$F_{\rm br}^{\rm (obs)} = F_{\rm br} \times \frac{t_{\rm br}}{t_{\rm lc}}. \tag{13}$$

Furthermore, when initially the temperature is rather large, $\approx 10^8$ K, the spectral slope between the Low and Medium Energy concentrator optics/spectrometers of *BeppoSAX* should be rather flat, while later, as the torus cools and its flux decreases, the spectral slope should also increase. Piro et al. (1999) find that, at the point where the re-burst is (fractionally) highest over the smooth afterglow, $\alpha = 0.4 \pm 0.6$ (i.e. consistent with a flat bremsstrahlung spectrum), while later they find $\alpha = 2.2 \pm 0.7$. Although there are large errors, the steepening of the spectrum through the re-burst appears to be significant. In view of the agreement of the duration time-scale, flux level and steepening of the spectral slope, we suggest that the observed re-burst in GRB 970508 is thus bremsstrahlung radiation from a torus of hot material, heated up, and then cooled down, by the photons produced by the impact of the burst ejecta.

We now need to cover our tracks by determining whether there are values of the total torus mass and volume that satisfy, together with $F_{\rm br}^{\rm (obs)} = 1 \times 10^{-11}\,{\rm erg\,s^{-1}\,cm^{-2}}$, also $\tau_{\rm T} \approx 1$ and $n \approx 10^{10}\,{\rm cm^{-3}}$ which we have assumed throughout. We assume a geometry whereby the torus has a volume $V = \delta\Omega R^2\,\delta R$, with the torus thickness $\delta R \leq R$, the torus distance from the explosion site. Since $\tau_{\rm T} = 0.6(M/1\,{\rm M_\odot})(10^{16}\,{\rm cm}/R)^2 4\pi/\delta\Omega$, we see that, for $M = 5\,{\rm M_\odot}$, $R = 10^{16}\,{\rm cm}$, $V = 10^{47}\,{\rm cm^3}$, $\delta R = 10^{14}\,{\rm cm}$ and $\delta\Omega \approx 4\pi$, we satisfy all constraints simultaneously: $\tau_{\rm T} \approx 2$ and $n = 4 \times 10^{10}\,{\rm cm^{-3}}$. From this we see that the torus need not be thin ($\delta\Omega \approx 4\pi$), which certainly agrees with expectations about the nature of exploding sources. Also, we notice that $t_{\rm br}/t_{\rm lc} \approx 4$, so that the duration of the bremsstrahlung cooling radiation is diluted by light crossing time effects.

Thermal expansion of the shell during the cooling phase is negligible, since the cooling time is of the order of the light crossing time, which is certainly shorter than the sound crossing time.

It is well known that GRB 970508 had an early optical detection, ≈ 0.2 d after the burst, which was dimmer than later (>1 d) detections (Sahu et al. 1998). Typical fluxes throughout the first 2 d are around 30 μJy, which far exceeds the optical component of the bremsstrahlung emission from the torus, which is in the range of ≈ 0.03 μJy. Thus the observed nearly simultaneous rise of X-ray and optical fluxes remains, within this model, a coincidence.

4 DISCUSSION

Beyond explaining the observed X-ray re-burst (and the Fe line, see below), the current model makes a number of interesting predictions. First, the secondary burst may be observable. We may expect these events to last a few thousand seconds, with fluxes in the range of 10^{-11} to $10^{-10}\,{\rm erg\,s^{-1}\,cm^{-2}}$. The spectra of these sources are also interesting: we argued above that the torus temperature is limited by pair creation, which would otherwise cause excessive radiative losses; thus we may expect the torus to reach a limiting temperature such that $\tau_{\rm T} \approx 1$, and a temperature of 5×10^8 K, which corresponds to a Compton parameter $y \approx 0.5$. We thus expect significant departures from the usual, power-law-like spectra of bursts. In particular, from sources that do not have time to cool down to $T_{\rm f}$ (equation (10)), so that the Comptonization of the secondary burst spectrum is time-independent, we expect to see a cut-off $\propto \exp(-h\nu/kT)$ beyond $h\nu = kT \approx 50$ keV, with a complicated, time-dependent non-power-law behaviour below this point (Rybicki & Lightman 1979). This exponential cut-off can be used as signature of unsaturated Comptonization, typical of the present model.

Another interesting consequence of this model is that the secondary burst may be seen even without its being preceded by the main gamma-ray burst. This would occur whenever we missed the (beamed) emission from the burst proper, but saw the isotropic emission from the re-burst. This might occur because in many models the beaming of the main burst is expected to be rather smooth, and one may conjecture that, while the total output may be $\approx 10^{52}$ erg close to the major axis, a total of 10^{51} erg remains to be emitted nearly isotropically. This would amply satisfy the energy requirements of the re-burst. The total expected fluences (up to $\approx 10^{-4}\,{\rm erg\,cm^{-2}}$ for distances smaller than that of GRB 970508) and durations ($\approx 10^3$ s) strongly remind one of the so-called fast X-ray transients, many of which last through several satellite orbits and have no identified counterparts (Grindlay 1999). A number of these events should become observable with planned new telescopes such as *SWIFT*.

An interesting question that one may ask is why observation of re-bursts is so rare: up to now, GRB 970508 and 970828 are the only two bursts for which such a phenomenon has been observed. So long as the torus is optically thin to bremsstrahlung, we see from equation (12) that the expected flux scales with distance from the explosion site as R^{-q}, where $q = 2$–3. Since we ignore the torus thickness, we consider the two limiting cases: $q = 3$, a uniformly filled sphere; and $q = 2$, an infinitely thin shell. This flux will appear with a time-delay R/c with respect to the burst, simultaneously with an afterglow that scales as t^{-p}, with $p \approx 1.3$. We see that the torus-to-afterglow flux ratio scales as t^{p-q}, with $p - q = -(0.7$–$1.7) < 0$. Thus the more distant the torus is, the less easy it is to detect it. However, since we have supposed that $\tau_{\rm T} \approx 1$ for $R \approx 10^{16}$ cm, further shrinking of the torus will make it less bright, not more; but it will have to compete with a simultaneously emitted afterglow that is brighter and brighter. So $R = 10^{16}$ cm is an ideal distance at which the torus could be located.

For the same parameters as above, Lazzati et al. (1999) have shown that the iron line can be interpreted as being due to purely thermal processes. Actually, Lazzati et al. showed that fluorescence and multiple ionization/recombinations can also account for the line, given suitable (but different!) thermodynamic conditions for the emitting plasma. However, we have shown in this paper that the thermodynamic conditions of the emitting torus are not free, but are essentially fixed by the requirement that the re-burst be fitted. We wish to stress that this is a much more demanding requirement, since the reality of the re-burst cannot be doubted, while that of the iron line is more questionable. It is, however, satisfying that the thermodynamic parameters thusly determined ($T = 10^8$ K, $n = 4 \times 10^{10}\,{\rm cm^{-3}}$) are precisely those that Lazzati et al. (1999) had to assume, in order to fit the line.

As a corollary, one may then understand why it is difficult to observe the iron lines. Lazzati et al. (1999) have derived the luminosity of the line as a function of the torus temperature: $\propto \exp(-8 \times 10^7\,{\rm K}/T) T^{-2.4}$. This luminosity has a peak for $T = T_{\rm m} = 3 \times 10^7$ K, and decreases steeply with increasing T. We see that $T_{\rm IC}^{(2)} \approx T_{\rm m}$, while $T_{\rm IC} \gg T_{\rm m}$. Thus it is only when the torus manages to cool down that it will find itself in ideal conditions for producing a bright iron line; we see from equation (10) that this occurs only for material that lies close to the explosion site. Otherwise, the torus material will remain in a hot state in which the line equivalent width is very small: ≈ 20 eV at $T = T_{\rm IC}$ (Bahcall & Sarazin 1978). We also remark that, even in the case in which the torus has managed to cool down to $T_{\rm m}$, after a time $t_{\rm br}$ it will further cool below $T_{\rm m}$, and the line flux will promptly decrease, thereby explaining the disappearance of the iron line in the observations of GRB 970508 (Piro et al. 1999).

Should the torus be located at larger radii, then we would expect the material to be hotter (from equation (10)), and the Fe line not to be observable, from the argument above. We thus expect inverse correlations of the time-delay after which the re-burst appears with the luminosity, and with the Fe-line equivalent width.

An alternative model for the anomalous behaviour of GRB 970508 has been proposed (Panaitescu, Mészáros & Rees 1998). In this alternative model there is no external material to cause a resurgence of the X-ray flux, and the peculiarities in the time-evolution of the optical afterglow are explained as a consequence of beaming. However, the anomalous variations in the X-ray flux can barely be followed (see especially their Fig. 2), and certainly there is no allowance either for the observed spectral variations of the X-ray flux during the first 2 d, or for the existence of an iron line.

Lastly, we would like to comment on the fact that we require a dense and abundant amount of iron-rich (for a redshift of $z = 0.835$!) material, at a small distance from the explosion site: $5\,M_\odot$ at $R = 10^{16}$ cm. This is clearly incompatible with all existing models of gamma-ray bursts, neutron star–neutron star/neutron star–black hole/ black hole–white dwarf mergers and hypernovae, except for supra-novae (Vietri & Stella 1998), which are preceded by a supernova explosion occurring between 1 month and 10 yr before the gamma-ray burst. With an average expansion speed of $3000\,\mathrm{km\,s^{-1}}$, this implies an accumulated distance of $R = 10^{15-17}$ cm. At this distance, one should find several solar masses (McCray 1993) with densities of the order of $10^{10}\,\mathrm{cm^{-3}}$, exactly as required by this independent set of observations.

REFERENCES

Bahcall J. N., Sarazin C. L., 1978, ApJ, 219, 781
Boettcher M., Dermer C. D., Crider A. W., Liang E. P., 1999, A&A, 343, 111
Ghisellini G., Haardt F., Campana S., Lazzati D., Covino S., 1999, ApJ, 517, 168
Grindlay J. E., 1999, ApJ, 510, 710
Lazzati D., Campana S., Ghisellini G., 1999, MNRAS, 304, L31
McCray R., 1993, ARA&A, 31, 175
Mészáros P., Rees M. J., 1998, MNRAS, 299, L10
Mészáros P., Laguna P., Rees M. J., 1993, ApJ, 415, 181
Metzger M. R. et al., 1997, Nat, 387, 378
Panaitescu A., Mészáros P., Rees M. J., 1998, ApJ, 503, 314
Perna R., Loeb A., 1998, ApJ, 501, 467
Piro L. et al., 1998, A&A, 331, L41
Piro L. et al., 1999, ApJ, 514, L73
Rees M. J., Mészáros P., 1992, MNRAS, 258, L41
Rybicki G. B., Lightman A. P., 1979, Radiative Processes in Astrophysics, J. Wiley & Sons, New York
Sahu K. C. et al., 1998, ApJ, 489, L127
Vietri M., Stella L., 1998, ApJ, 507, L45
Yoshida A., Namiki M., Otani C., Kawai N., Murakami T., Ueda Y., Shibata R., Uno S., 1999, ApJ, submitted

This paper has been typeset from a TEX/LATEX file prepared by the author.